Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress

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Cheung, Stephen S., and Tom M. McLellan. Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. *J. Appl. Physiol.* 84(5): 1731–1739, 1998. —The purpose of the present study was to determine the separate and combined effects of aerobic fitness, short-term heat acclimation, and hypohydration on tolerance during light exercise while wearing nuclear, biological, and chemical protective clothing in the heat (40°C, 30% relative humidity). Men who were moderately fit [(MF); <50 ml·kg^{-1}·min^{-1} maximal O_2 consumption; n = 7] and highly fit [(HF); >55 ml·kg^{-1}·min^{-1} maximal O_2 consumption; n = 8] were tested while they were euhydrated or hypohydrated by ~2.5% of body mass through exercise and fluid restriction the day preceding the trials. Tests were conducted before and after 2 wk of daily heat acclimation (1-h treadmill exercise at 40°C, 30% relative humidity, while wearing the nuclear, biological, and chemical protective clothing). Heat acclimation increased sweat rate and decreased skin temperature and rectal temperature (T_{re}) in HF subjects but had no effect on tolerance time (TT). MF subjects increased sweat rate but did not alter heart rate, Tre, or TT. In both MF and HF groups, hypohydration significantly increased T_{re} and heart rate and decreased the respiratory exchange ratio and the TT regardless of acclimation state. Overall, the rate of rise of skin temperature was less, while ΔT_{re}, the rate of rise of T_{re}, and the TT were greater in HF than in MF subjects. It was concluded that exercise-heat tolerance in this uncompensable heat-stress environment is not influenced by short-term heat acclimation but is significantly improved by long-term aerobic fitness.

heat exhaustion; temperature regulation; hypohydration

IN SITUATIONS of compensable heat stress, where the evaporative heat-loss capacity (E_{max}) of the environment exceeds the evaporative heat loss required (E_{req}) to maintain a thermal steady state, repeated heat exposures over 4 days to 2 wk have been shown to produce cardiovascular and thermoregulatory adaptations which result in decreased physiological strain and increased tolerance during exercise in the heat (13, 14). Classic adaptations after heat acclimation include an increase in sweating response and a decrease in heart rate (HR), core temperature and skin temperature (T_{sk}), and perceived exertion during exercise in the heat (35). Two factors known to modify the dynamics of heat acclimation are the aerobic fitness and hydration status of the individual. The efficacy of a heat-acclimation program may be dependent on the fitness status of the individual. Fit individuals adapt more rapidly to heat exposure, with an inverse relationship reported between maximal aerobic power ($\dot{V}O_{2max}$) and the number of days required to reach a heat-acclimated state (24). However, individuals of low- to moderate-aerobic fitness, without any prior adaptations to heat from long-term training, may experience a greater potential benefit from a period of heat acclimation than fit individuals experience, as larger decreases in HR and rectal temperature (T_{re}) postacclimation were observed in subjects with low as opposed to high $\dot{V}O_{2max}$ (6, 30). Any thermoregulatory benefits derived from heat acclimation during exercise in the heat are overwhelmed by the elevated stress imposed by hypohydration (HY). Whereas heat acclimation produced a decrease in core temperature when subjects were euhydrated (EU), HY of 5% body weight, regardless of acclimation status, resulted in a significantly higher final T_{re} compared with EU condition (6, 27).

Some of the adaptations to long-term training or habitual exercise, including an increase in evaporative heat-loss capacity along with a decrease in resting core temperature, are common to those adaptations observed with heat acclimation, such that improvements in aerobic fitness, typically characterized by $\dot{V}O_{2max}$, have been associated with an improved tolerance to exercise in the heat (see Ref. 3). Cadarette et al. (6) reported that, during compensable heat stress, a decreasing cardiovascular and thermoregulatory strain occurred with increasing fitness before acclimation, although only cardiovascular benefits achieved with fitness were retained postacclimation. In a cross-sectional design (34), a lower HR and aural temperature and T_{sk}, along with increased tolerance time (TT), were reported during compensable heat stress in very fit subjects compared with subjects of average fitness.

The wearing of protective clothing in the heat can result in a situation of uncompensable heat stress, where evaporative heat loss is limited and is less than that required to maintain thermal equilibrium (15). In these situations, increased aerobic fitness or heat acclimation may be of limited effectiveness in decreasing physiological strain or prolonging tolerance. Because of the limited water vapor permeability through the clothing, it is possible that the increased sweat production in trained or heat-acclimated subjects may increase physiological strain by promoting a faster rate of dehydration rather than increasing evaporative heat loss (22). After 8 wk of aerobic training or 6 days of heat acclimation, little or no improvements in physiological responses or TT have been observed in subjects wearing nuclear, biological, and chemical (NBC) protective clothing (1). In addition, no differences in aural temperature or T_{sk} and only minor improvements in TT were observed in very fit subjects compared with subjects of average fitness during exercise in the heat while wear-

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ing NBC clothing (34). However, the metabolic rate used to evaluate the changes in heat tolerance in these two studies may have produced heat exhaustion before a significant amount of heat transfer could occur through the clothing layers. Thus, the physiological benefit of an increased sweat rate (SR) with aerobic fitness or heat acclimation may have been negated, and the influence of $\dot{V}O_{2max}$ and fitness status on tolerance to uncompensable heat stress remains unclear. In contrast, 12-day heat-acclimation programs produced a significant improvement in exercise-heat tolerance during light exercise in the heat while wearing NBC clothing (2, 20). In these studies, subjects underwent progressive dehydration with no fluid replacement. Recently, we reported that fluid replacement during uncompensable heat stress resulted in a significantly lower HR and an increased TT (10). Thus, it remains unknown whether benefits from heat acclimation would be present where fluid replacement is provided.

The purpose of the present study was to determine the separate and combined effects of heat acclimation, aerobic fitness, and hydration status on exercise-heat tolerance during uncompensable heat stress. Subjects of both moderate fitness (MF) and high aerobic fitness (HF) exercised in a hot environment while wearing the NBC clothing both while EU and while HY by ~2.5% of body mass. In particular, we investigated the following questions. *1)* Do subjects with a high level of aerobic fitness derived from long-term training and habitual exercise have an improved tolerance during light exercise compared with individuals of MF and sedentary lifestyle? *2)* When fluid replacement is provided, will heat acclimation produce similar benefits as observed previously without fluid replacement? *3)* Is the magnitude of improvement with heat acclimation greater in subjects of MF? *4)* Does mild HY impair exercise-heat tolerance regardless of fitness or heat-acclimation status?

METHODS

Subjects

Fifteen healthy men between the ages of 18 and 40 yr, who were recruited from the university population or the military community, participated in the study. Subjects underwent a medical examination and were informed of all details of the experimental procedures and the associated risks and discomforts before they provided their consent. Subjects were grouped into two general categories, either MF or HF, on the basis of both an interview concerning their exercise habits and the results of a treadmill test of maximal aerobic power. MF subjects were either inactive at the time of the study or engaged in physical activity only on an irregular basis; they had a $\dot{V}O_{2max}$ between 40 and 50 $ml \cdot kg^{-1} \cdot min^{-1}$. All MF subjects agreed to abstain from regular aerobic activities for the duration of the experiment. HF subjects were defined as those engaged in a regular program of physical activity and having a $\dot{V}O_{2max}$ in excess of 55 $ml \cdot kg^{-1} \cdot min^{-1}$.

Experimental Design

The experimental protocol and instrumentation used in the present study were approved by the Ethics Review Committees of the University of Toronto and the Defence and Civil Institute of Environmental Medicine (DCIEM). Testing was conducted at the DCIEM from late September to March to limit initial heat acclimation through casual exposure to high ambient temperatures. On five separate occasions, each subject performed a heat-stress test (HST), which consisted of walking on a motorized treadmill in a hot environment [40°C, 30% relative humidity (RH), wind speed <0.1 m/s] while wearing the Canadian Forces NBC protective clothing ensemble. On the afternoons before the sessions were conducted, subjects exercised in the heat until they became dehydrated by 2.5% of their body mass. For all subjects, the first session was used as a familiarization trial, and the results were discarded. A minimum of 1 wk separated experimental trials to avoid the effects of partial heat acclimation (5).

Responses to the HST were evaluated during exercise on the treadmill at 3.5 km/h and 0% grade while the subjects' level of hydration were manipulated. After the dehydration protocol, subjects were either rehydrated to baseline body mass overnight (EU) or they maintained the 2.5% decrease in body mass overnight (HY). During all HST, subjects underwent a fluid-replacement program consisting of 200 ml of water every 15 min, with the water temperature maintained near 37°C. The order in which the different conditions were presented was randomized to minimize order effects or the effects of partial heat acclimation. To counterbalance order effects, the order of the hydration trials for each subject was reversed after the heat-acclimation period.

After an HST in each of the conditions (EU and HY), all subjects underwent a 2-wk heat-acclimation program. For 5 days/wk, subjects walked on a motorized treadmill at 4.8 km/h and a grade between 3 and 7% for 1 h while wearing combat clothing and the NBC overgarment in the same hot environmental conditions (40°C, 30% RH) as were employed for the HST. The intensity was chosen such that the increase in T_{re} during the 1 h was ≥1.5°C on the first day of acclimation. A similar heat acclimation program of 12 days resulted in an increase in sweat rate (SR) and a decrease in HR and core temperature during subsequent exercise in a hot environment (20).

On the completion of the 2-wk heat-acclimation period, all subjects again performed an HST in the EU and HY conditions. Between the first and second postacclimation HST, all subjects performed two to three heat-acclimation sessions to maintain their heat-acclimated status.

NBC Protective Clothing

The Canadian Forces NBC protective clothing ensemble worn in all trials consisted of shorts, T-shirt, socks, combat shirt and trousers, running shoes, semipermeable NBC overgarment, gas mask and cannister, and impermeable rubber gloves and overboots. Total mass of the ensemble was ~6.0 kg. To allow some sweat evaporation, there is limited mass penetration of charcoal-filtered air through the fabric. Thermal resistance and the Woodcock vapor-permeability coefficient of the ensemble, as determined on a heated and wetted manikin at a wind speed of 1.12 m/s, were 0.291 $m^2 \cdot °C \cdot W^{-1}$ and 0.33, respectively (16).

Determination of $\dot{V}O_{2max}$

$\dot{V}O_{2max}$ was determined on a motorized treadmill by using open-circuit spirometry before and after the series of experiments in the climatic chamber. After subjects ran for 3 min at a self-selected pace, the treadmill grade was increased 1% each minute to 10%. Thereafter, increases in treadmill speed and grade of 0.22 m/s (0.8 km/h) or 2%, respectively, alter-

ıted each minute until the subject could no longer continue. ıbjects were given verbal encouragement throughout the st. $\dot{V}O_{2max}$ was defined as the highest 30-s O_2 consumption O_2) observed during the incremental test. HR was moni- red throughout the incremental test from a telemetry unit olar Vantage XL). The value recorded at the end of the ercise test was considered to be the individual's maximal R. Body fatness was estimated from skinfold measurements using a gender-specific regression equation developed from drostatic measurements of body density (12).

hydration Protocol

An identical dehydration and overnight protocol was em- yed in a previous investigation in this laboratory and was ınd to be effective in manipulating the hydration status of ə subjects (10). In the afternoons before the exercise ısions, subjects reported to the laboratory at ~1330 h for ə dehydration protocol. This allowed ~15 h for body fluid npartments to stabilize between the dehydration protocol d the HST. Dehydration sessions took place in the same vironmental chamber (40°C, 30% RH) that was used for the ST. Weights, measured when subjects were both nude and ɔssed (shorts, socks, shoes), were recorded before entry into ə chamber. Subjects walked on a motorized treadmill at an ərcise intensity (4.5–6.0 km/h, 3–7% grade) that induced ight loss at a rate of 0.8–1.5 kg/h. T_{re} and body mass were nitored throughout the dehydration, and subjects were noved from the chamber when they lost 2.5% of their seline body mass.

Nutrition was controlled for all trials by providing subjects ch a set meal plan consisting of PowerBar meal replace- nt bars. For subjects undergoing EU trials, sufficient torade was provided immediately after the dehydration sion to replace the amount of weight loss. Subjects in the ' trial were also instructed to drink 600 ml/h of Gatorade or ces that evening and at least 600 ml in the morning before y reported to the laboratory. Subjects undergoing the HY ıls were given a total ration of 800 ml of Gatorade, based on ɔected basal weight losses over a 15-h period.

ssing and Weighing Procedure

Preparation of subjects, insertion of the rectal thermistor, l placement of skin thermistors have been detailed previ- ly (19). Before the dressing procedure, subjects remained an upright posture for 10 min; a 5-ml blood sample was ained within 90 s of the subjects' lying down. Plasma ıolality was calculated from plasma concentrations of cose, sodium, and blood urea nitrogen (Nova Ultra Stat, va Biomedical). Before subjects entered the chamber, their ght, both nude and dressed, was recorded. After subjects ered the chamber, their skin and rectal thermistor- nitoring cables were connected to a computerized data- uisition system. Then the subjects began to exercise. an values over 1-min periods for T_{re}, and a 12-point ghted mean T_{sk} ($\bar{T}_{sk}$) (32) were calculated, recorded, and ıted by the data-acquisition system. HR was recorded every 5 min from the Polar Vantage XL unit. After each trial was completed, subjects' weight while dressed was recorded within 1 min after their exit from the chamber. Nude weight was recorded within 5 min after subjects undressed and were toweled dry.

Differences in nude and dressed body masses before and after each trial were corrected for respiratory and metabolic weight losses (see *Gas-Exchange Analyses*). The amount of sweat produced was calculated as pretrial nude body mass − posttrial nude body mass (corrected) + water given. Evaporative sweat loss from the clothing was calculated as pretrial dressed mass − posttrial dressed body mass (corrected) + water given.

TT

TT for all trials was defined as the time until Tre reached 39.3°C, HR remained at or >95% of maximal HR for 3 min, dizziness or nausea precluded further exercise, either the subject or the experimenter terminated the experiment, or 4 h had elapsed.

Gas-Exchange Analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation, $\dot{V}O_2$, and carbon dioxide production from a 2-min average obtained every 15 min. To collect expired air, an adapter was attached to the respirator. Respiratory water loss was calculated by using the measured $\dot{V}O_2$ and the equation of Mitchell et al. (21). Metabolic body mass loss was calculated from the $\dot{V}O_2$ and the respiratory exchange ratio (RER) by using the equation described by Snellen (31).

Statistics

Data are presented as means ± SD. A three-factor (period × hydration × time) repeated-measures ANOVA was used to compare T_{re}, T_{sk}, and HR of the HF and MF subjects undergoing the short-term heat acclimation. A two-factor (period × hydration) repeated-measures ANOVA was used to compare the responses of TT, body mass changes, SR, plasma osmolality, metabolic rate, and RER. When a significant F-ratio (corrected for the repeated-measures factor) was obtained, a Newman-Keuls post hoc analysis was performed to isolate differences among treatment means. After separate data analyses within either the HF or the MF group, a comparison was performed across the two groups to detect differences in exercise-heat tolerance as a result of long-term fitness. For all statistical analyses, the 0.05 level of significance was used.

RESULTS

The physical characteristics of the subjects are shown in Table 1. The HF and MF subjects were similar in age and height. As expected, the HF subjects were distinguished from the MF subjects by their much higher

ɔle 1. *Physical characteristics of the subjects in moderately fit (MF) and highly fit (HF) groups*

oup	n	Age, yr	Height, m	Body Mass, kg	Body Fat Content, %	Surface Area, m^2	Surface Area-to-Mass, $m^2 \cdot kg^{-1} \cdot 10^2$	$\dot{V}O_{2max}$, $ml \cdot kg^{-1} \cdot min^{-1}$	
								Pre	Post
F	7	27.3 ± 6.9	1.78 ± 0.08	92.9 ± 5.0*	20.9 ± 4.0*	2.11 ± 0.11*	2.28 ± 0.05*	46.1 ± 2.9*	46.0 ± 2.9*
F	8	27.9 ± 6.5	1.77 ± 0.03	76.8 ± 4.3	11.5 ± 2.9	1.94 ± 0.14	2.56 ± 0.08	59.8 ± 2.8	59.5 ± 4.1

alues are means ± SD. n, No. of subjects; $\dot{V}O_{2max}$, maximal O_2 consumption; Pre, preacclimation; Post, postacclimation. *Significantly ırent from HF group, $P < 0.05$.

$\dot{V}O_{2max}$ and a lower body fat content, respectively. Furthermore, the HF subjects were generally smaller than the MF group, with a lower body mass and a smaller surface area. The effects of the heat-acclimation regimes on physiological responses during the first and the final day of exposure are summarized in Tables 1 and 2. Acclimation did not induce an increase in aerobic capacity, with no changes in $\dot{V}O_{2max}$ following acclimation in either the HF or MF group (Table 1). MF subjects experienced a significantly lower HR along with a higher SR during the final day of acclimation (Table 2). Adaptation also occurred in HF individuals, with an increased SR along with a decreased T_{re} and HR in response to the heat-acclimation exercise on *day 10*.

Tolerance to the HST was determined by time, physiological end points imposed for ethical considerations, or subject exhaustion. The reasons for trial termination are presented in Table 3. None of the trials approached the 4-h time limit. For MF subjects, the large majority of the experimental trials were terminated because of exhaustion, as determined by the subject or the experimenter. Only four trials, all by the same subject, were terminated because of reaching the ethical limit for HR. In contrast, HF subjects generally terminated trials because of reaching the ethical limit for core temperature (39.3°C). Voluntary exhaustion often coincided with reaching the T_{re} limit; however, in many cases, the subjects felt that they were not completely exhausted and could have continued further. Every attempt was made to thoroughly familiarize all subjects with the protocol and to eliminate the influence of learning or order effects. Some subjects in both groups were very familiar with the NBC clothing and the HST because they had been subjects in previous heat experiments in this laboratory. The initial familiarization session served to accustom all subjects to the protocol and to any associated discomforts before the actual test. All subjects were highly motivated, and little doubt existed about the presence of exhaustion and imminent collapse at the end of the HST.

The hydration schedule after the dehydration protocol was successful either in reinstating EU or in maintaining HY overnight (Table 4). In EU trials, body mass returned to baseline levels overnight, and mass was similar for all EU trials. The HY protocol resulted in a relative decrease in mass of 1.9 to 2.8% in the HF and MF groups, respectively, compared with the pre-EU trial. HY also increased serum osmolality in both groups.

Table 2. *Sweat rate (SR), change in rectal temperature (ΔT_{re}), final rectal temperature (T_{re}), and final heart rate (HR) in MF and HF subjects at start and end of heat-acclimation period*

	MF		HF	
	Day 1	*Day 10*	*Day 1*	*Day 10*
SR, l/h	1.35 ± 0.21	1.54 ± 0.21*	1.67 ± 0.37	1.92 ± 0.48*
SR, l/°C	0.95 ± 0.24	1.02 ± 0.21	1.03 ± 0.28	1.28 ± 0.42*
ΔT_{re}, °C	1.54 ± 0.34	1.54 ± 0.21	1.66 ± 0.23	1.56 ± 0.31
Final T_{re}, °C	38.70 ± 0.24	38.53 ± 0.15	38.75 ± 0.23	38.54 ± 0.20*
Final HR, beats/min	167.3 ± 15.1	159.9 ± 19.0*	156.1 ± 13.6	146.9 ± 15.3*

Values are means ± SD. *Significantly different from *day 1*; $P < 0.05$.

Table 3. *Reasons for termination of heat-stress tests in MF and HF groups*

Group	n	Time	T_{re}	Heart Rate	Volition
MF	7	0	0	4	24
HF	8	0	24	0	8

Table 5 summarizes some of the physiological responses to the HST. In both groups, one major adaptation to the acclimation program was an increased SR during the HST. However, because of the difficulty in water vapor transfer through the NBC ensemble, no significant changes in evaporation rate were observed. Heat acclimation did not significantly prolong TT in either fitness group. While heat acclimation had no effect on exercise-heat tolerance, HY resulted in a significant degree of impairment regardless of acclimation status. While end-point T_{re} was unaffected by hydration status within either group, the initial T_{re} for MF was significantly higher before HY trials. Overall, in both the HF and MF groups, HY resulted in a significantly shorter TT, regardless of acclimation status. HY resulted in a significantly lower RER during HY in both the MF and HF groups. This decrease in RER was not because of a difference in glucose availability before exercise; there were with no differences in serum glucose levels between EU and HY.

The T_{sk}, T_{re}, and HR responses to the HST are presented in Figs. 1-3, respectively. In the MF group, despite the cardiovascular and sweating adaptations observed over the course of the acclimation program, no differences in T_{sk}, T_{re}, and HR response were evident during the HSTs after the 2-wk acclimation period. Interestingly, the acclimation period had a greater impact on the thermoregulatory responses to the HST in subjects who were already HF aerobically. In HF subjects, the acclimation program was successful in decreasing the thermoregulatory strain during the postacclimation HSTs, with a main effect found for a lower T_{sk} and T_{re}.

HY significantly impaired thermal and cardiovascular responses to the HST in both fitness groups. In both MF and HF, T_{re} was significantly higher overall during HY than EU trials, with the primary factor in MF being an elevated initial T_{re} (Fig. 2). In the HF group, HY trials also resulted in an elevated rate of rise of T_{re}. HR response to the HST was influenced by hydration status in both fitness groups (Fig. 3), with a significant elevation in HR in both the HF and MF groups during HY. In MF subjects, HY also elicited a higher rate of rise of HR. In MF subjects, T_{sk} was significantly elevated during HY. In HF subjects, HY did not affect overall T_{sk}, but the initial increase in T_{sk} over the first 25 min was significantly slower during post-EU compared with all other conditions.

Table 4. *Absolute and relative (to pre-EU) nude body mass and serum osmolality in MF and HF groups during heat-stress tests before and after heat acclimation*

	MF				HF			
	Preacclimation		Postacclimation		Preacclimation		Postacclimation	
	EU	HY	EU	HY	EU	HY	EU	HY
Body mass, kg	93.74 ± 5.52	90.97 ± 5.60*	93.61 ± 5.90	91.10 ± 5.47*	76.80 ± 9.80	74.76 ± 9.81*	76.79 ± 9.95	75.36 ± 10.05*
Body mass loss, %	0.00 ± 0.00	−2.78 ± 0.92*	−0.14 ± 1.15	−2.64 ± 0.61*	0.00 ± 0.00	−2.04 ± 0.52*	0.00 ± 0.71	−1.87 ± 0.75*
Osmolality, mosmol/kgH_2O	286.9 ± 3.8	292.7 ± 4.0*	286.6 ± 3.7	292.6 ± 3.9*	286.2 ± 2.6	292.5 ± 3.6*	285.4 ± 1.8	291.4 ± 3.5*

Values are means ± SD. EU, euhydration; HY, hypohydration. Significant difference between HF and MF groups in body mass. *Significant main effect of hydration, $P < 0.05$.

When the results in the HF and MF groups during the HST are compared, the HF group had a greater change in T_{re} (ΔT_{re}), a result of both a significantly lower initial T_{re} and a higher final T_{re}. The greater ΔT_{re} was a major contributing factor to an overall increased HST in HF subjects. The overall rate of rise in T_{sk} was significantly lower in HF than in MF subjects. No significant between-group differences were observed in cardiovascular response, SR, and evaporation rate during the HST.

DISCUSSION

Heat acclimation, hydration status, and aerobic fitness are factors that have been demonstrated to influence exercise-heat tolerance during compensable heat stress, where the E_{max} exceeds the E_{req} (see Refs. 3, 26, 3 for reviews). The purpose of the present study was to extend the investigation of these factors into an environment of uncompensable heat stress, where the E_{req} exceeds or matches the E_{max}. Even very light exercise in the heat while wearing clothing with limited permeability to water vapor will result in uncompensable heat stress (15), and the light exercise employed in the present study was sufficient to produce a heat-stress index (HSI) of ~2.5 (HSI = E_{req}/E_{max}). Under these conditions, when fluid replacement is present, heat acclimation had no influence on exercise-heat tolerance in both MF and HF individuals. In contrast, HY before exercise significantly impaired tolerance regardless of acclimation status or aerobic fitness. Long-term aerobic fitness resulted in a significant improvement in exercise-heat tolerance, regardless of hydration or acclimation status.

Significant physiological adaptations occurred in both the HF and MF groups over the 10 days of the heat-acclimation protocol, notably an increased SR which was also evident during the full encapsulation conditions of the HST. The physiological mechanisms underlying this increased sweating response could not be determined with the present methodology. However, during the HST, the increased sweat production did not result in an elevation in evaporative heat loss or a slowing of the rate of T_{re} increase in either group because of the limited water vapor permeability of the NBC clothing. In uncompensable heat stress, therefore, the higher SR from heat acclimation is a negative adaptation which, instead of enhancing evaporative heat loss and attenuating thermal strain, increases the rate of dehydration and physiological strain (22).

In addition to the evaporative impairment caused by the protective clothing, several explanations may account for our finding of a lack of significant improvement in exercise-heat tolerance after heat acclimation. One explanation is that the subjects may not have been fully acclimated by our program. According to the regression equation for the attainment of heat acclimation presented by Pandolf et al. (24), the MF and HF subjects in the present study should have reached a plateau in response by 7 and 4.5 days, respectively. However, hot-wet acclimation may produce a slower plateau rate. In addition, full heat acclimation in a hot-humid environment required >1 h exposure/day

Table 5. *SR, evaporation rate, average metabolic rate, RER, tolerance time, and initial and final T_{re} for MF and HF groups*

	MF				HF			
	Preacclimation		Postacclimation		Preacclimation		Postacclimation	
	EU	HY	EU	HY	EU	HY	EU	HY
SR, l/h	1.04 ± 0.26	1.08 ± 0.19	1.33 ± 0.40†	1.27 ± 0.27†	1.30 ± 0.34	1.28 ± 0.35	1.43 ± 0.39†	1.42 ± 0.35†
Evaporation rate, l/h	0.33 ± 0.04	0.30 ± 0.04	0.34 ± 0.04	0.31 ± 0.06	0.38 ± 0.13	0.36 ± 0.08	0.40 ± 0.14	0.35 ± 0.08
Average metabolic rate, W/m²	181.6 ± 11.9	185.6 ± 13.2	185.1 ± 14.8	182.9 ± 12.2	175.1 ± 23.8	178.0 ± 24.0	175.8 ± 15.6	174.6 ± 21.2
RER	0.88 ± 0.06	0.82 ± 0.04*	0.85 ± 0.04	0.82 ± 0.04*	0.88 ± 0.05	0.82 ± 0.03*	0.88 ± 0.04	0.84 ± 0.04*
Tolerance time, min	96.6 ± 19.6	78.3 ± 16.9*	101.4 ± 11.4	80.6 ± 18.0*	114.5 ± 27.4	100.9 ± 20.4*	115.6 ± 18.4	110.5 ± 29.7*
Initial T_{re}, °C	36.93 ± 0.27	37.26 ± 0.27*	36.96 ± 0.26	37.24 ± 0.32*	36.85 ± 0.22	36.99 ± 0.22	36.74 ± 0.19	36.83 ± 0.22
End-point T_{re}, °C	38.77 ± 0.27	38.69 ± 0.30	38.79 ± 0.31	38.63 ± 0.31	39.15 ± 0.18	39.20 ± 0.08	39.14 ± 0.21	39.21 ± 0.06

Values are means ± SD. RER, respiratory exchange ratio; significant difference between HF and MF groups in tolerance time, initial T_{re}, and end-point T_{re}. *Significant main effect of hydration, $P < 0.05$; †Significant main effect of acclimation, $P < 0.05$.

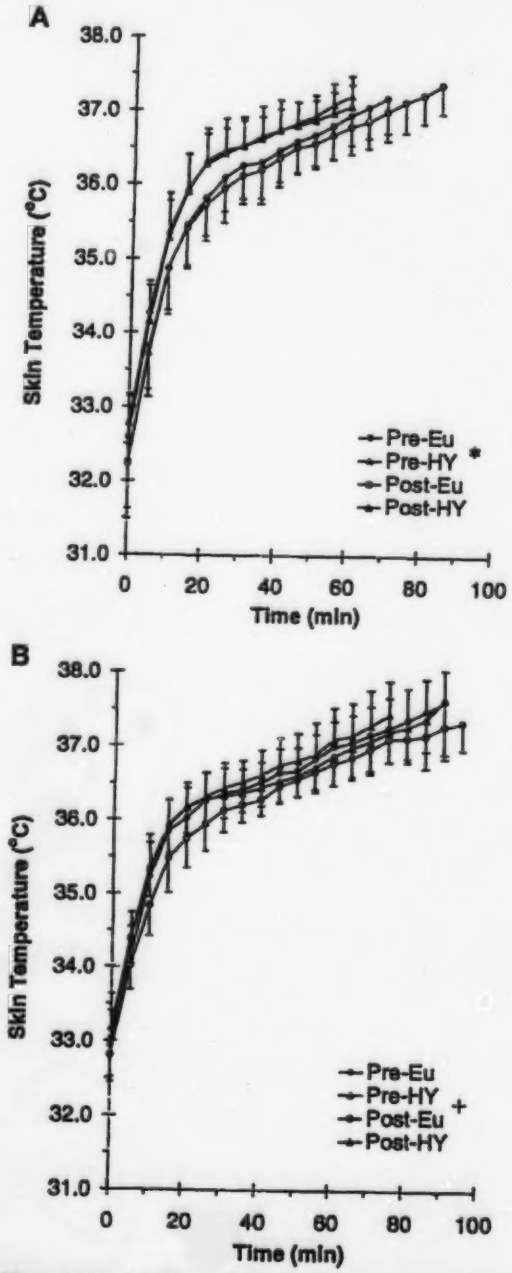

Fig. 1. Mean skin temperature response of moderately fit (MF; $n = 7$; *A*) or highly fit (HF; $n = 8$; *B*) subjects to heat stress test while either euhydrated (Eu; circles) or hypohydrated (HY; triangles), before (solid symbols) and after (open symbols) 2 wk of heat acclimation. Overall skin temperature was significantly higher in MF than in HF. Values are means ± SD. *Significant main effect of hydration (*A*), $P < 0.05$. +Significant main effect of heat acclimation (*B*), $P < 0.05$.

(14). Counteracting these arguments are the reports of significant adaptations while wearing clothing with limited water vapor permeability after 1 h of heat acclimation for 4–6 (29) or 12 (20) days. In the present study, comparison of responses to the heat-acclimation exercise on *days 9* and *10* revealed a plateau in SR and in the HR and T_{re} after 60 min in both HF and MF. In addition, because an increased SR is one of the physiological adaptations with the slowest time course (17), the elevated SR in both groups suggests the attainment

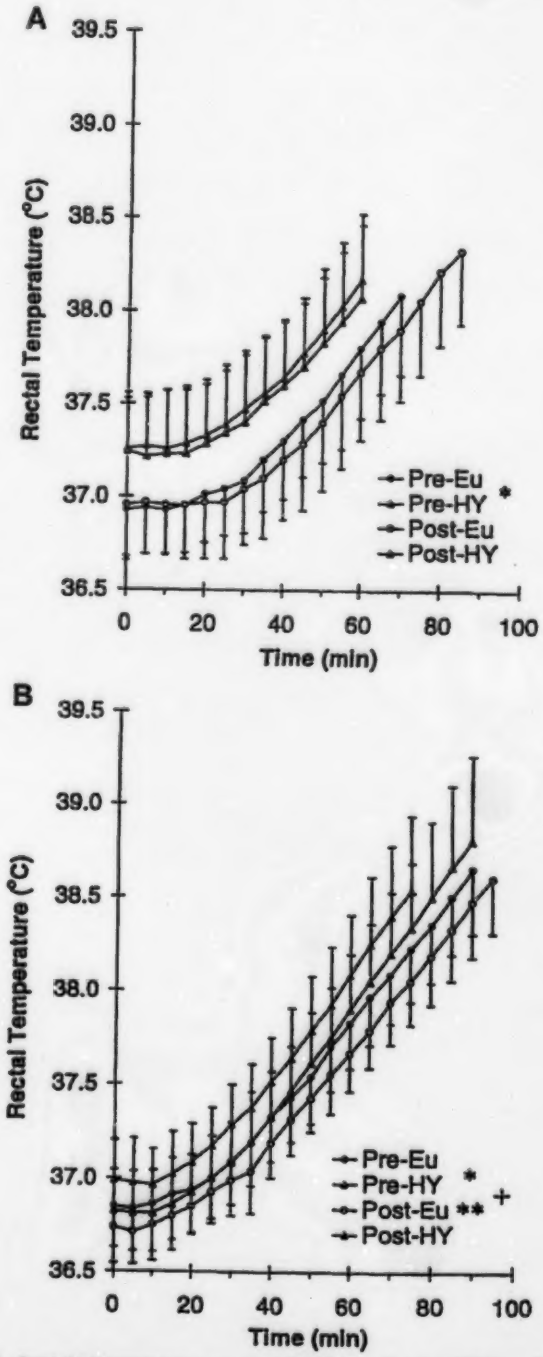

Fig. 2. Rectal temperature response of MF ($n = 7$; *A*) or HF ($n = 8$; *B*) subjects to heat stress test while either Eu (circles) or HY (triangles), before (solid symbols) and after (open symbols) 2 wk of heat acclimation. Values are means ± SD. *Significant main effect of hydration, $P < 0.05$. **Significant hydration × time interaction, $P < 0.05$. +Significant main effect of acclimation, $P < 0.05$.

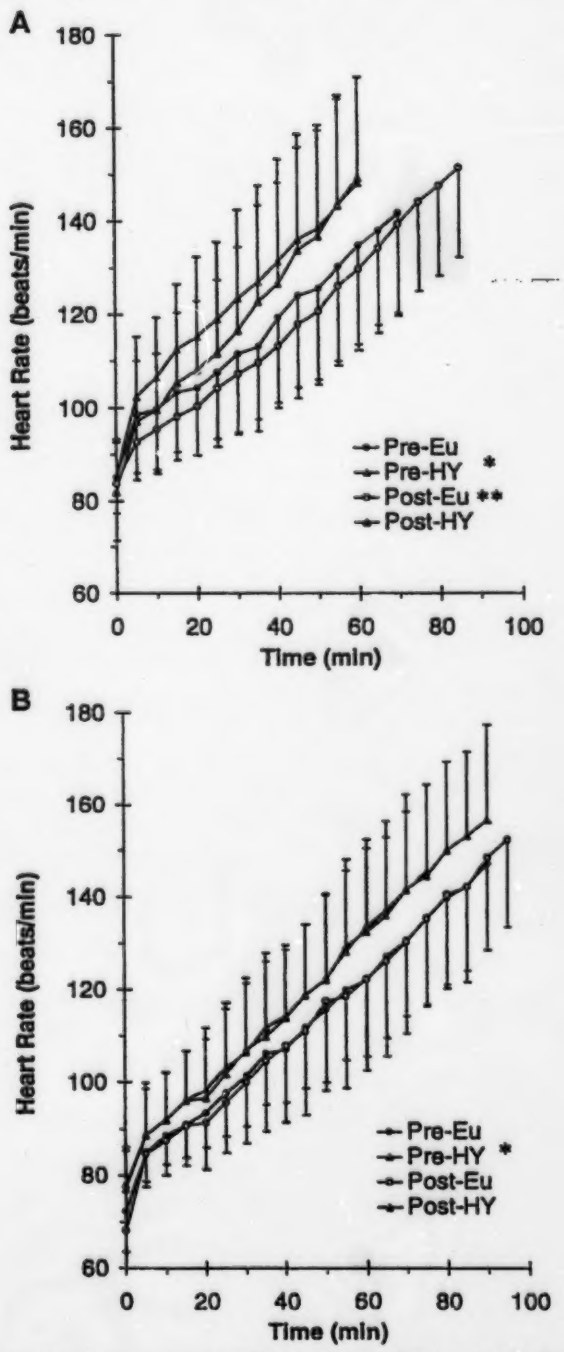

Fig. 3. Heart rate response of MF ($n = 7$; *A*) or HF ($n = 8$; *B*) subjects to heat stress test while either Eu (circles) or HY (triangles), before (solid symbols) and after (open symbols) 2 wk of heat acclimation. Values are means ± SD. *Significant main effect of hydration, $P < 0.05$. **Significant hydration × time interaction, $P < 0.05$.

of near-maximal adaptations in other physiological systems. We are therefore confident that the subjects achieved a nearly complete state of heat acclimation.

Any benefits accruing from heat acclimation in an uncompensable heat-stress environment may have been masked by the presence of fluid replacement. In the present study, the finding of no heat-acclimation effects on exercise-heat tolerance in both fitness groups contrasts with two previous studies in our laboratory that demonstrated a decrease in physiological strain and an increase in TT during exercise in the heat with NBC clothing after heat acclimation with (20) or without (2) NBC clothing. The disparity in the effects of acclimation may be caused by the fact that, whereas subjects in the previous studies were not provided with any fluid replacement during the HST, water was provided to subjects in the present study at regular intervals. Fluid replacement has been demonstrated to reduce physiological strain during exercise in the heat (8) and specifically to decrease cardiovascular strain and to increase TT while exercising in the heat with NBC clothing (10). Thus, the fluid replacement may have extended exercise-heat tolerance during the preacclimation HST to near the maximum possible given the uncompensable heat-stress environment, thereby limiting the amount of improvement that could be observed with subsequent heat acclimation. If this is the case, it would reinforce the importance of fluid replacement in an uncompensable heat-stress environment regardless of fitness or acclimation status.

The deleterious influence of HY on exercise performance in thermoneutral and hot environments has been reviewed in detail elsewhere, and it is well known that HY is associated with an increase in HR, T_{re}, and ratings of perceived exertion (7, 26). HY also altered the metabolic response to the HST, with a significantly lower RER during the HST in both the MF and HF groups. This decrease in RER has been reported previously (11, 28) and was not because of a decrease in glucose availability, as no differences were observed in serum glucose levels between EU and HY (unpublished observations). In a EU state, heat acclimation significantly decreased final T_{re} in environments with a HSI of ~1.0 (27). However, in the same study, HY significantly increased thermal strain, regardless of acclimation status, with similar final T_{re} both before and after heat acclimation. The present study extends these findings to a more severe uncompensable heat-stress environment. Compared with EU, HY resulted in a decreased TT, regardless of fitness or acclimation status, with an elevated resting T_{re} in MF and an increased rate of rise in T_{re} during the HST in HF subjects. Therefore, not only fluid replacement during exercise but also hydration status before exercise appears to take precedence over acclimation status in determining physiological strain during uncompensable heat stress.

Exercise-heat tolerance was improved by fitness, regardless of hydration or heat-acclimation status, with an average combined TT of 110 and 88 min in HF and MF, respectively. These observations support the general consensus that an association exists between the level of cardiorespiratory fitness and improvements in physiological responses to exercise in a hot environment (3). In subjects who exercised at a higher intensity in the heat while wearing NBC clothing, trained subjects also had a slight increase of TT compared with

untrained subjects (34). The present study used both the $\dot{V}O_{2max}$ and the level of regular physical activity to define the division of subjects into two distinct fitness groups. The inclusion of activity level as a selection criterion was prompted by the observation that $\dot{V}O_{2max}$ by itself was only moderately correlated with heat tolerance and that the amount of regular physical activity may be a better indicator of the presence of training-induced adaptations to heat exposure (4, 18, 25).

One major difference in the response to the HST between the two fitness groups was the significantly higher degree of hyperthermia and ΔT_{re} tolerated by the HF group. HF subjects had both a significantly lower initial and a higher end-point T_{re} than the MF subjects, resulting in a ΔT_{re} over the course of the HST of 2.3°C in the HF subjects compared with 1.6°C in MF subjects. Extrapolating an increase of the ΔT_{re} in the MF group by 0.7°C, and given their linear rate of T_{re} increase of ~1.0°C/45 min, the MF TT would increase by 31.5 min. In contrast, if the ΔT_{re} of the HF group decreasedby 0.7°C, the linear rate of T_{re} increase of ~1.0°C/40 min would decrease their TT by 28 min. With an actual observed difference in overall TT of ~22 min between the MF and HF groups, it is evident that the difference in TT between the two fitness groups could be largely accounted for by the difference in ΔT_{re}.

The difference in tolerance to hyperthermia is also evident from the disparity in the reasons for the termination of the HST (Table 3). The large majority of the HSTs with HF subjects were terminated because of the individuals' reaching the ethically imposed limit of 39.3°C T_{re}, whereas nonfit subjects generally reached voluntary exhaustion at a T_{re} well below 39.3°C. All subjects underwent an initial familiarization trial involving the complete experimental protocol, and no effects of order or training were observed on TT or endpoint T_{re}. HF individuals may be capable of tolerating a higher level of subjective discomfort or physiological strain because of their regular program of physical activity. Alternatively, a given combination of T_{re} and T_{sk} may produce a greater degree of subjective discomfort in nonfit subjects. While thermal convergence of core temperature and T_{sk} may not be a reliable determinant of tolerance in an uncompensable heat-stress environment (23), a particular T_{sk}-core temperature difference or the increased rate of T_{sk} increase could result in greater discomfort in MF subjects. HF subjects may also be better able to tolerate high levels of skin wettedness and the effects of hidromeiosis (9).

In summary, this study leads to the following observations regarding exercise-heat tolerance in an uncompensable heat-stress environment. *1*) High aerobic fitness from long-term training and habitual exercise is of significant benefit. *2*) When fluid replacement is provided, heat acclimation does not provide significant benefit regardless of fitness status. Fluid replacement may, therefore, be an effective substitute for a heat-acclimation program. *3*) The magnitude of improvements in physiological strain with heat acclimation are greater in those subjects with high aerobic fitness, but the improvements are still insufficient to improve exercise-heat tolerance. *4*) Mild HY of 2–3% of body mass results in significant impairment, regardless of fitness or heat acclimation status.

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